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Experimental Identification of Local and Nonlocal Turbulence in Magnetically Confined Plasma

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Nonlocal transport phenomena, where disturbances propagate far beyond local interaction scales, represent a long-standing cross-disciplinary challenge due to the difficulty in directly observing the mediating structures. Such phenomena are observed in diverse complex systems, including large-scale eddies in oceans and the atmosphere, turbulent jets, and preferential channels in porous media, which transport heat, tracers, or contaminants far beyond predictions of simple diffusion models. In high-temperature plasma physics, nonlocal transport is both a theoretical curiosity and a practical reality, with experimental observations revealing phenomena like multiple flux-gradient relations and turbulence spreading below the critical gradient. These multi-scale behaviors are often attributed to "mediators" that link turbulent structures over extended regions, but direct visualization of these structures has remained elusive due to their small size, transience, and disorder.

This research successfully overcomes this long-standing experimental gap by employing high-resolution spatiotemporal diagnostics in a magnetically confined plasma to directly observe the turbulent structures mediating nonlocal transport. Experiments were conducted using the Large Helical Device (LHD)[1-3]. Since nonlocal transport is identifiable only during transient phases of perturbation experiments, Modulated Electron Cyclotron Heating (MECH) experiments were performed, systematically varying the duration of heat pulses to investigate their effects on propagation velocity. Electron temperature gradients were measured by electron cyclotron emission, while ion-scale turbulence and electron-scale turbulence were measured using Doppler reflectometry and backscattering diagnostics, respectively.

The study experimentally identified and separated two coexisting turbulent components with complementary roles:

Nonlocal Turbulence: This component appears in the low-frequency range (10-20 kHz) immediately after heating begins. It is gradient-insensitive and is excited almost simultaneously throughout the entire plasma region within 2 ms. Cross-correlation analysis of electron-scale turbulence revealed strong correlations between spatially distant points shortly after heating, with interactions occurring within 100 µs across the plasma, indicating that this low-frequency nonlocal turbulence facilitates spatial coupling and acts as a mediator.

Local Turbulence: This component appears in the high-frequency range (50-100 kHz) and is synchronized with the local electron temperature (T_e) gradient. It propagates from the plasma core to the peripheral region over approximately 10 ms, concurrently with the T_e gradient, and is responsible for carrying the bulk heat flux.

The impact of the mediator was quantitatively assessed using a scaling law relating heat-pulse speed (v) and pulse duration(s): $v \propto s^{-1.06}$. This relationship demonstrates that stronger departures from steady-state enhance long-range propagation. Shorter heat pulses were observed to propagate faster and exhibit nonlocal transport characteristics, deviating from steady-state behavior. Conversely, longer pulses (approximately 100 ms or more) resembled steady-state perturbations, displaying slower propagation velocities comparable to local transport speeds. These findings indicate that while both local and nonlocal turbulence coexist, the rapid, nonlocal transport component, mediated by nonlocal turbulence, dominates the heat pulse immediately after heating, followed by a local transport component that propagates on the transport timescale.

This research provides the first unambiguous experimental evidence for the long-hypothesized mediator pathways, validating key theoretical predictions in plasma physics. The significance of these results extends beyond plasma physics, offering critical insights toward resolving a long-standing experimental gap across various natural science domains. The findings provide the first laboratory benchmark for analogous mediators believed to exist in ocean eddies, atmospheric jets, and preferential flow paths in disordered media, and offer an experimental strategy to isolate transport-bearing structures in other complex systems. Incorporating such mediators into multiscale models will enhance predictive capabilities in scenarios where rapid, long-distance redistribution governs system behavior, from climate dynamics to energy technologies. Ultimately, recognizing and measuring nonlocal interactions as fundamental aspects of transport brings us closer to a unified, cross-disciplinary framework for describing and controlling the evolution of far-from-equilibrium matter.

References

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